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December 5, 2005
05471-L-001

Ms. Nancy Reimer
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SUBJECT: Analysis of Flywheel Housing Failures

Dear Ms Reimer:

This letter serves as my report into the failure of the flywheel housings experienced by Trans-Spec Truck Service, Inc. It includes the results of inspections, laboratory evaluations and engineering analysis.

1.0 BACKGROUND

The flywheel housings in question are cast aluminum components designed and fabricated by Caterpillar and bolt on the rear end of their 3176, C10 and C12 diesel engines. The housing is attached using 12 M12 x 1.75 (metric dimension) bolts that are threaded into the cast iron engine block. The transmission then bolts on the other end of the flywheel housing. The 3176 engine was released in 1989 with the release of the C10 and C12 in 1994/95 timeframe. All of these engines use the same design aluminum flywheel housing utilizing the same bolting patterns. Therefore, the flywheel housings are interchangeable on all these engine models. Over the years the horse power and maximum torque ratings of the engines have evolved from 280 hp and 1050 ft-lbs of torque up to 430 hp and 1650 ft-lbs of torque. This constitutes a 54% increase in hp and a 57% increase in maximum torque over the years. The Trans-Spec trucks were rated at the higher horsepower and torque. No design modifications to the flywheel housings to account for these increases in horsepower and torque were identified nor was any testing performed on the housings to verify their suitability for these higher ratings.

Trans-Spec Truck Service, Inc. operated vehicles that contained these types of engines and flywheel housings. The vehicles were manufactured by Sterling Truck Corporation. Over the course of several years numerous flywheel housings have either cracked or had the bolts that attach the flywheel housing to the rear of the engine loosen necessitating replacement.

Altran Solutions was contracted to investigate the cause of these failures. This report summarizes the results of that investigation.

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2.0 LABORATORY INVESTIGATION

Altran Solutions was provided with three flywheel housings for evaluation. The housings are identified as #21, #35 and C-12-2. Housings #21 and #35 were identified with these numbers prior to receipt at Altran. We were informed that #21 was removed from a C-12 engine in a Sterling Truck because it became loose and cracked. We were also informed that housing #35 was removed from a 3176 engine and replaced with a new housing due to cracking. Finally, we were told that housing #C12-2 was a recent replacement of a damaged housing and it was removed for examination after the truck was involved in an accident. The identification #C12-2 was provided by Altran.

The laboratory analysis of the housings consisted of visual inspections, photo-documentation, nondestructive examination using dye penetrant, chemical analysis, fractography using stereo and scanning electron microscopy (SEM) and hardness testing.

2.1. Housing #21 Visual Inspection

Figure 1 and Figure 2 show photographs of flywheel housing #21 showing the engine side and transmission side, respectively. The bolt holes are also shown labeled for reference. There are 12 bolt holes and two alignment dowel pin holes. The bolt holes are 13 millimeter diameter through holes to accept the M12 x 1.75 metric bolts grade 10.9. The bolts pass through from the transmission side and into threaded holes in the cast iron engine block.

The visual inspection revealed several features. First, the majority of the bolt holes exhibited deformation on the inside surfaces corresponding to impressions from the bolt threads. Second, there is an area of wear on the engine side indicating contact and relative movement with another engine component. Finally, one crack was observed originating from one of the bolt holes and another from flange mounting surface.

Damage of the bolt holes corresponding to deformation by the bolt threads was observed in bolt holes 3, 4, 5, 6, 8, 10, 11 and 12. Figure 3 and Figure 4 show photographs of bolt holes 8 and 11, respectively and are representative of the type of damage to the bolt holes. The images depict the thread impressions on the inside surfaces of the bolt holes. Note that these are through holes and are not threaded. The thread impressions are the result of movement of the flywheel housing causing contact with the threads severe enough to cause this type of permanent deformation.

Cracking in the flywheel housing was also observed. Figure 4 shows the damage to the inside surface of bolt hole 11 as well as a crack emanating from the hole. The crack is visible across the entire machined face for mounting against the engine block. Figure 5 shows another crack originating from the flange mounting face near to bolt hole 12. This crack extends across the ~3/8" flange face and about 1/2" into the housing.

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The area of wear is approximately 11-inches long by 3-1/2-inches high located on the engine block side of the flywheel housing and is depicted in Figure 1. This area is consistent with a fretting type wear appearance in which two surfaces are under a contact load with a small amount of relative motion between the two. The depth of the wear area varies across the area with maximum depths measured at about 0.040 to 0.045-inches.

2.2. Housing #21 Penetrant Examination

The engine side mounting surface of flywheel housing #21 was examined using dye penetrant to identify other areas of cracking. Dye penetrant is a non-destructive technique to highlight crack-like defects and imperfection in materials. It consists of spraying a dye that penetrates into cracks in materials. A developer is then applied that provides contrast to any dye located in cracks.

Figure 6 shows a photograph typical of the penetrant examination of housing #21. It depicts two areas with distinct cracks. One in bolt hole 11 and the other in the flange face near bolt 12. One other crack was identified located in bolt hole 12. Figures 7-10 show close-up images of these cracks as highlighted by the dye penetrant.

2.3. Housing #21 Chemical Analysis

A sample was removed from Area A (depicted in Figure 1) for chemical analysis and hardness testing. According to Caterpillar specification 1E1047 for heat-treated aluminum sand and permanent mold castings the chemical composition is similar to UNS A03560. The results are summarized in Table 1 and compared to the requirements of the Caterpillar specification.

Table 1. Summary of Chemical Analysis of Housing #21.

Element	Composition, %	
	CAT 1E1047 (356)	Housing #21
Silicon	6.5-7.5	6.67
Iron	0.6 max	0.35
Copper	0.25 max	0.17
Manganese	0.35 max	0.17
Magnesium	0.20-0.45	0.33
Zinc	0.35 max	0.14
Titanium	0.25 max	0.12
Lead	0.05 max	-
Others (each)	0.05 max	0.02 (Cr)
Total all others	0.15 max	
Aluminum	Balance	balance

The results in Table 1 show that the chemical analysis of flywheel housing #21 is consistent with Caterpillar specification 1E1047.

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2.4. Housing #21 Hardness

The same sample removed for chemical analysis was also subjected to hardness testing. The hardness was measured using the Rockwell "B" scale (HRB). Three hardness tests were performed with the results of: 55.4, 52.8 and 53.3 HRB giving an average of 53.8 and a standard deviation of 1.48. Caterpillar specification 1E1047 for aluminum casting has a requirement for a permanent mold casting with a T6 temper (identified as a requirement on the flywheel housing drawings) that the typical hardness consist of 80 on the Brinnel scale using a 500 kg load and a 10 mm ball. This value converts to an equivalent HRB value of 40 using conversion numbers for wrought aluminum taken from ASTM E-140. The results of the hardness tests show that the material in housing #21 meets the hardness requirements of Caterpillar specification 1E1047.

2.5. Fractography of Housing #21

The visual examination of flywheel housing #21 revealed three areas of cracking. The visual appearance of these cracks are typical of fatigue cracking. To confirm this, the crack in bolt hole 12 was removed and the fracture surface examined under stereo and scanning electron microscopy. Figure 10 shows the flywheel housing after the removal of the sample as well as a close-up photograph of the sample.

After removal, the sample was cut with a saw to leave a small remaining un-cracked ligament in order to facilitate opening of the crack to expose the fracture surfaces, a normal forensic technique. Figure 11 shows a photograph of the two mating fracture surfaces. Visible are the saw cuts along two edges of the sample. Also visible are small areas of relatively shiny material that are the fractures of the un-cracked ligaments. These areas were holding the specimen together prior to opening and represent the base material with no fatigue crack or saw cut. It also represents the fracture morphology of the base material in an overload condition. Finally, the majority of the surfaces consist of slightly rough fractures covered with a dark, tightly adhered surface layer. The morphology of the fracture is typical of that of a fatigue crack in a cast aluminum material. That is, slightly rough with various undulations. Since the microstructure of a cast material is not as homogenous as wrought materials fatigue crack propagation is typically a bit more circuitous and rough than in wrought materials. Specific fatigue crack propagation features, such as striations, are difficult to resolve, particularly with an oxidized surface.

The fracture surfaces were examined under high magnification using the scanning electron microscope. The samples were cleaned only with acetone prior to examination. Figure 12 shows SEM images representative of the fatigue crack fracture surface at low and high magnifications. The images do not show any distinctive features due to the surface layer, most likely an oxide layer from exposure to the local environment inside the flywheel housing. Figure 13 shows an SEM image at high magnification of the fracture of the remaining ligament. This image shows a

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dimpled morphology characteristic of a ductile overload fracture. No evidence of this type of ductile overload appearance was observed on the cracked fracture surface.

2.6. Housing #35 Visual Inspection

Figure 14 shows an overall photograph of the engine side of flywheel housing #35. The visual inspection revealed some features that are common to housing #21. First, cracking was observed in the housing. Cracks were observed emanating from bolt hole #11 and #12 and at the flange housing, as in housing #21. A large crack was also observed on the top of the housing near bolt hole 2. Second, there is a similar area of wear on the engine side indicating contact and relative movement with another engine component. No major damage to the inside surfaces of the bolt holes, in the form of thread impressions, was observed.

Figure 15 and Figure 16 show close-up photographs of the cracks originating in bolt holes 11 and 12, respectively. It is evident that these cracks are significantly larger than those in housing #21, and they are oriented in the same relative directions. The crack at hole 11 propagates into the opening for the starter and the crack at bolt hole 12 progresses about 2-inches towards the outside surface of the housing. Figure 17 shows the crack at the top of the housing near bolt hole 2. A close inspection shows that the crack starts below bolt hole 4 and propagates to the top of the housing under bolt hole 2 and progresses around the top giving a total length of about 6-inches.

The area of wear is approximately 12-inches long by 3-1/4-inches high located on the engine block side of the flywheel housing and is depicted in Figure 14. This area is consistent with a fretting type wear appearance in which two surfaces are under a contact load with a small amount of relative motion between the two. The depth of the wear area varies across the area with maximum depths measured at about 0.015-inches.

2.7. Housing #35 Penetrant Examination

The engine side mounting surface of flywheel housing #35 was examined using dye penetrant to identify other areas of cracking. Figure 18 shows a photograph typical of the penetrant examination of the crack at bolt hole 11 and Figure 19 shows the cracks at bolt hole 12. Finally, Figure 20 shows the large crack at the top of housing #35 as revealed by the penetrant.

No hardness, chemical analysis or fractography was performed on housing #35 or #C12-2. No visual cracks or wear was observed on housing C12-2.

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3.0 DISCUSSION

The results of the laboratory inspection and analysis of the aluminum flywheel housings show that they failed by cracking in the region of bolt holes and/or loosening of the bolts that attach the housing to the engine block. There was also anomalous wear located on the housing. The laboratory analysis also showed that the cracking observed in the housings is the result of fatigue. Fatigue in metallic materials is the initiation and propagation of cracks resulting from a cyclic or oscillating applied stress. This means that a component can fail at stresses considerably lower than its tensile strength (the stress at which failure will occur under a non-cyclic stress) when it is exposed to a vibrating state. This is a problem because a component that was initially placed in service, in the as-designed condition, and fabricated to meet all of the design specifications could still fail prematurely if the cyclic stress state was not properly accounted for in the original design.

Fatigue is an insidious problem in the design of materials, in particular aluminum. Most steels have what is referred to as an "endurance limit" or "fatigue limit". This is the magnitude of the cyclic stress below which fatigue failure will not occur. Thus, if the magnitude of the cyclic stresses likely to occur during use is below the endurance limit of the material, then fatigue failure will not occur. However, with aluminum, there is no such definable endurance limit. In the ASM Handbook Volume 19 "Fatigue and Fracture" D. Cameron states:

The "infinite life" aspect of this approach is related to the asymptotic behavior of steels, many of which display a fatigue limit of "endurance" limit at a high number of cycles (typically $>10^6$) under benign environmental conditions. Most other materials do not exhibit this response, instead displaying a continuously decreasing stress-life response, even at a great number of cycles (10^6 to 10^9), which is more correctly described by a fatigue strength at a given number of cycles.

In the same volume M. Mitchell states:

Although an "endurance limit" is generally observed for many steels under constant-stress-amplitude testing, such a limit does NOT [emphasis added by Mitchell] exist for high-strength steels of such nonferrous materials as aluminum alloys

As a result, when designing with aluminum that will be exposed to a cyclic stress state, such as that experienced by a flywheel housing, particular care must be given to assure that the cyclic stresses are considerably lower than any fatigue strength published for aluminums. This can be accomplished through proper engineering design. Proper design to preclude fatigue failure should involve specific knowledge of the stresses in the component (obtained by analysis) as well as the use of recognized standards and in-house design guidelines that places limits on the maximum allowable stress that can occur.

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Information provided by Caterpillar in the course of this investigation also revealed cracking at the same locations and bolt loosening problems with this style aluminum flywheel housing other than those inspected in our laboratory. This indicates a history of problems other than those experienced by Trans-Spec. Caterpillar provided some information regarding the design and analysis of the C10/C12 flywheel housings. The specified material of construction is given in Caterpillars' specification 1E1047 "Aluminum Casting-High strength-Heat Treated" with a T6 temper fabricated using the permanent mold process. The designation is similar to that of UNS A03560 and is a common cast aluminum. This specification also provides a tensile strength requirement of 228 MPa (33,000 psi) and a yield strength requirement of 152 MPa (22,000 psi). The tensile strength is the stress at which fracture will occur and the yield strength is the stress at which permanent deformation will occur. Note that the Caterpillar technical information is provided in metric SI units and the corresponding English equivalents will be provided in parentheses. Also provided was a table of information called "G-accelerations for Use in Analysis of Engine Supports, Fan Drives, and Component Supports and Structures". The entries for the Truck-on highway and Truck-off highway requirements are reproduced in Table 1.

Table 2. G-Accelerations Provided by Caterpillar

APPLICATION	FATIGUE CALCS.			LOW CYCLE CALCS.		
	Vert.	Fore-aft	Side-s	Vert.	Fore-aft	Side-s
Truck- on highway	1±2.5	0±1	0±1.5	1±5	0±4	0±2
Truck- off highway	1±3	0±1	0±1	1±8	0±3	0±3

What these numbers provide are accelerations that are to be used in the engineering analysis of the components. No specific information was provided as to what different types of analyses are performed to differentiate between the "Fatigue calcs" and "Low Cycle Calcs". Further, no information was provided to define what Caterpillar uses for the allowable stresses for this aluminum material when analyzed using the above G-acceleration loads.

A structural analysis was provided by Caterpillar that was "*... the only one pertaining to a C12 flywheel housing that it had, so it serves as an example, but it was just an example of one of many*". Thus, the analysis provided by Caterpillar is a basis for the typical analysis performed on the C12 flywheel housing. No information or analysis was provided that demonstrated that any analysis was performed on the C10/C12 flywheel housing concurrent with the time of original manufacture. Only this one analysis was provided by Caterpillar and according to a date on one of the pages it was performed on 06/03/02 which is after problems with the flywheels housings were first reported by Trans-Spec Truck Service, Inc.

The analyses provided by Caterpillar are a Finite Element Analysis (FEA) and a bolt joint analysis (BJA). The FEA is a computer model of the flywheel housing geometry, material and loading conditions. The analysis is based on a transmission that weighs 834.25 kg (1,839 lbs) and subjected to 4G down and 2G up loads. Finally, the bolts used in the analysis are M14 in size. Given these conditions, the maximum stress determined

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by the Caterpillar analysis occurs under the 4G down condition with a magnitude of 292.8 MPa (42,460 psi). The results of the Caterpillar FEA analysis for this load case are presented in Figure 21. Since the material has a tensile strength of 228 MPa (33,000 psi) and the calculated stress is 292.8 MPa (42,460 psi), the stress therefore exceeds the tensile strength by almost 30%. Thus, the flywheel housing would instantly crack at that location. Further, the location of the highest stress occurs at bolt hole 11 with stresses almost as high at bolt hole 12. These are the exact locations cracking was observed in the flywheel housings examined. Finally, the summary of the analysis stated that the stress level in the flywheel housing is high and could be the cause of failure under fatigue loading.

No acceptance criteria were provided by Caterpillar for the analysis nor was any discussion of the results provided. Therefore, to provide interpretation of the results the analysis will be analyzed using experience and accepted design practices. Information provided by Caterpillar documents that this analysis was based on a 834.25 kg (1,839 lbs) transmission that is about three times the weight of the transmissions in the Trans-Spec vehicles. Also, according to the information provided in Caterpillar documents, the G-loads applied are that for an off-road truck rather than an on-road truck. Therefore, these conditions differ from the C10/12 flywheel housing and transmission in the Trans-Spec vehicles. What is typically done in these types of analyses, and in accordance with accepted engineering practices, is to take the results from one analysis and scale them proportional to other load cases. This will allow the stress to be determined for the lighter transmission and for other assumed G-loads.

However, it still does not address what is an acceptable level of stress in the flywheel housing. Neither industry standards nor any in-house design guidelines regarding the level of allowable stress in the material were provided by Caterpillar. Analysis results without any acceptance criteria are meaningless. Since this basic information was not provided by Caterpillar, experience and accepted engineering practice was used to refer to other accepted national/international codes and standards as a basis for allowable stresses. The most universally accepted safety code is the American Society of Mechanical Engineers Boiler and Pressure Vessel Code (ASME B&PVC) and the ASME Piping codes. These standards provide one of the most thorough listings of materials and their associated allowable stress levels under different loading conditions and temperature exposures. Thus, the information in this code can be used as a sound foundation for setting allowable stress limits that will assure safe and reliable operation, without premature failure. In summary, no information was provided as to how the FEA results were interpreted, no acceptance criteria were provided, no backup information regarding the analytical process was supplied, and no analysis of how the flywheel housing/transmission configuration of a C10/12 engine responds was provided. Thus, accepted engineering practice and experience was used to interpret the results provided.

When a structural analysis is performed the expected normal operating loads as well as occasional upset loads need to be identified and determined to be used as input in the analysis of a structure or component such as the flywheel housing. The results of these analyses are then compared to the allowable stresses for each condition based on the

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material of construction. The AMSE code provides allowable stresses for the aluminum material used in the construction of the flywheel housing. For UNS A03560 cast aluminum with a T6 temper with a minimum tensile strength of 228 MPa (33,000 psi) the allowable stress is given as a function of the temperature as follows:

Table 3. Allowable Stresses for A356.0-T6 Cast Aluminum

Temperature, °F	Allowable Stress, MPa	Allowable Stress, psi
Up to 100	66.5	9,500
150	64.1	9,300
200	58.6	8,500
250	44.1	6,400
>250	-	-

Note that for temperatures above 250 °F no allowable stress is given which means that the material is not recommended for those elevated temperature applications. Given the severe operating conditions of the flywheel housing, attachment to a hot engine and its proximity to an exhaust line it is prudent to assume an operating temperature above ambient. For the case of this analysis it is assumed that the housing could experience temperatures up to 200°F, so the allowable stress for the material is 58.6 MPa (8,500 psi).

The results of the FEA can be scaled to account for differences in transmission weight and G-loads. The weight of the transmissions in the Trans Spec vehicles is estimated to be 317.5 kg (700 lbs), given a transmission weight of 605 lbs, ~25 lbs for the clutch housing, ~20 lbs for oil and ~ 50 lbs for the shift controls, output yoke and other miscellaneous appearances. This is 38.1% of the 834.25 kg (1,839 lbs) weight used in the analysis. Thus, the results of their analysis can be scaled down by a factor of 0.381 to obtain the results for the Trans Spec transmission. Further, if different G-loads are to be evaluated then the results can be further scaled up or down accordingly.

The first condition to evaluate is for the case of the highest expected occasional load. This is given in Table 2 under the "Low Cycle Calcs" column with a vertical G-load of 1 ± 5 . This means that the analysis should be performed with a G-load of 4 in the upward vertical direction and 6 in the downward vertical direction. The analysis provided that resulted in the highest stress was the result of 4G down loading so that result can be scaled to 6G down by multiplying the results by a factor of 6/4 or 1.5. The results can then be scaled for the actual transmission weight by applying the factor of 0.381 giving a scaled result of $1.5 \times 0.381 = 0.572$. Therefore, taking the maximum stress obtained in the analysis of 292.8 MPa (42,460 psi) and applying the scale factor of 0.572 gives a maximum stress of 167 MPa (24,200 psi).

These results can then be compared to the allowable stress presented earlier of 58.6 MPa (8,500 psi) for operation at 200°F. It should first be noted that the maximum stress of 173 MPa (25,100 psi) exceeds the yield strength of 152 MPa (22,000 psi) indicating that under a 6G load there will be localized deformation in the region of the highest stress at the bolt holes. It also exceeds the allowable stress of 58.6 MPa (8,500 psi) by almost a factor of three. However, since this is an occasional upset load (my interpretation of the G-load